Detection of left ventricular hypertrophy by multichannel magnetocardiography

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1 Introduction

Left ventricular hypertrophy (LVH) is a powerful independent risk factor for cardiac morbidity and mortality [1]. Although LVH itself may be symptomless, its detection is likely to contribute to the treatment of the patient. Thus, the detection of LVH is a clinical priority.

The most widely used methods for detecting LVH are 12-lead electrocardiography (ECG) and echocardiography. The ECG criteria for LVH, however, have low sensitivity at clinically acceptable levels of specificity [2]. Echocardiography, on the other hand, suffers from interobserver and intraobserver variability [3]. Only a few studies have been published on detecting LVH by magnetocardiography (MCG) [4, 5, 6, 7].

The changes, on which the diagnosis of LVH by ECG is based, are an increase in duration and amplitude of the QRS complex due to an increase in LV mass [8], and abnormalities in ventricular repolarization [9]. Vectorcardiographic QRS- and T-loops, which in normal hearts tend to be parallel, are typically more divergent in LVH. In ECG this change can be seen as so-called *LV strain* pattern, i.e., downsloping convex ST-segment, which evolves into an asymmetrical inverted T-wave, see Fig. 1. [8]

In a normal heart, the main direction of ventricular activation is radial. In a hypertrophied heart, the contribution of tangential currents is increased. MCG is primarily sensitive to currents tangential to the chest, and thus MCG could provide information complementary to ECG for LVH detection. [10]

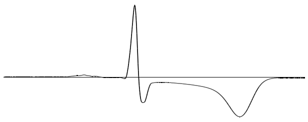

Figure 1: *Electrocardiographic LV strain. Notice the depressed ST-segment and inverted T-wave, i.e., the polarity of the T-wave is opposite to the main QRS complex.*

Another benefit of MCG compared to ECG might be the attenuation of electromagnetic field. Patients with LVH are often obese, and the higher signal amplitude due to LVH may be cancelled by increased attenuation. The magnetic permeability of human tissues is close to that of a vacuum, and the MCG signals can be scaled with the distance between the source and the device. For ECG the scaling would require more accurate information on the thoracic structure and conductivity, as the constants of attenuation of ECG signals vary significantly with tissue.

In this study, the point of interest was to develop a method for detecting LVH by multichannel magnetocardiography.

2 Methods

2.1 Patients

The patient population of this study consisted of 20 female and 27 male subjects with essential hypertension and/or aortic stenosis. The patients were 63±12 (mean±standard deviation) years old (females 64 ± 12, males 62 ± 11). Mean left ventricular mass (LVM) in echocardiography was 233±63 g (206±59, 252 ± 59) and LVM/BSA (body surface area) was 123 ± 32 g/m^2 (117 ± 31, 128 ± 31). The limits of LVM/BSA for echocardiographic LVH were 104 g/m^2 for females and 118 g/m^2 for males. With these partitions, there were 14 females (70%) and 16 males (59%) with echocardiographic LVH in the patient population.

2.2 MCG Recordings

All magnetocardiographic measurements were performed in a magnetically shielded room in the BioMag laboratory at Helsinki University Central Hospital, with a 67-channel cardiomagnetometer [11]. The center of the cardiomagnetometer was placed at 4th intercostal space, 5 cm to the left from the center of sternum. The 12-lead ECG was measured simultaneously with the MCG.

The signals recorded in 5 minute measurements were selectively averaged. The signal averaged data were interpolated to correspond to the data of 33 axial channels measuring $\partial B_z/\partial z$, where B_z is the component of the magnetic field perpendicular to the bottom of the dewar [12]. All the magnetocardiographic indices for detecting LVH were calculated using the interpolated data.

The center of the heart was approximated to locate 12 cm below the center of the dewar. The signals on each channel were scaled to correspond a recording distance of 12 cm from the center of the heart. Here, the magnetic field was approximated to attenuate inversely to the square of distance.

The onset and offset of QRS complex and offset of T-wave were defined on each channel. QRS onset and offset were determined by Simson's algorithm [13] and T-wave offset by an algorithm described in Ref. [14].

2.3 Indices for Detecting LVH

It was hypothesized that with increasing LVM the amplitude and duration of QRS complex increase. In MCG, the divergent de- and repolarization vectors were hypothesized to lead to *MCG strain*, i.e., opposite orientations of isointegral maps over the QRS complex and the T-wave. Also, QRS-T discordance, i.e., opposite polarities of QRS complex and T-wave, was hypothesized to increase with higher LVM.

QRS area

The QRS complex area on each channel was calculated by integrating the absolute value of MCG signal over the QRS complex. The areas were summed up over the measurement grid to obtain the QRS area index.

T-wave integral

The MCG signal was integrated on each channel from QRS offset to T-wave offset. If there was no discordance of the T-wave, i.e., if the polarities of the main QRS complex and the T-wave were same, the absolute value of the integral was added to the sum over the measurement grid. In the case of QRS-T discordance the absolute value of the integral was subtracted from the sum.

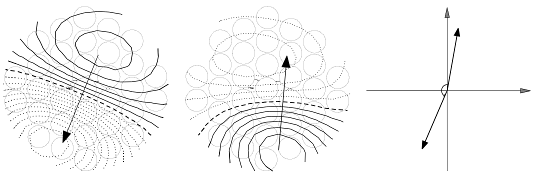

Figure 2: *The calculation of MCG strain. Left: an isointegral map over the QRS complex, direction angle of the gradient vector (arrow) is 247°. Middle: an isointegral map over the T-wave, direction angle of the gradient vector is 80°. Right: the angle between the direction vectors of the gradients was used as the index. The value of the MCG strain index here is 167°. Step of the isointegral contours is 1.0 pT for the QRS map and 0.5 pT for the T-wave map.*

QRS-T Combination

The information in the QRS complex and the T-wave were combined by subtracting the T-wave integral index from the QRS area index.

MCG Strain

Isointegral maps over both the QRS complex and the T-wave were calculated for all subjects. The magnetic field map angle was calculated as the orientation of the highest spatial gradient of the signal in the measurement plane [15], see Fig. 2. The MCG strain was defined as the angle between the T-wave gradient vector and the QRS gradient vector.

Electrocardiographic Indices

In the 12-lead ECG, Sokolow and Lyon's and Romhilt and Estes' indices as well as Cornell voltage and 12-lead voltage sum were calculated.

3 Results

The values of sensitivity at matched, clinically acceptable level of specificity (83% for females and 81% for males) are shown in Table 1 for MCG and ECG indices. For females and males the specificities correspond to one and two false positive subjects, respectively. The sensitivities and specificities of Sokolow-Lyon voltage, Cornell voltage and

Table 1: *Sensitivities of MCG and ECG indices at matched specificity. QRS = QRS area, T = T-wave integral, QRS-T = QRS-T combination, strain = MCG strain, S-L = Sokolow-Lyon voltage, Cornell = Cornell voltage, R-E = Romhilt-Estes index, VS = 12-lead voltage sum.*

Females

	MCG		ECG	
spec	index	sens	index	sens
83	QRS	64	S-L	25
83	T	71	Cornell	58
83	QRS-T	78	R-E	33
83	strain	64	VS	45

Males

	MCG		ECG	
spec	index	sens	index	sens
81	QRS	56	S-L	57
81	T	69	Cornell	69
81	QRS-T	81	R-E	79
81	strain	69	VS	77

Table 2: *Sensitivities and specificities of the ECG indices at their conventional cut-off values. S-L = Sokolow-Lyon voltage (3.5 mV), Cornell = Cornell voltage (females 2.0 mV, males 2.8 mV), R-E = Romhilt-Estes index (5 points).*

	Females		Males	
index	spec	sens	spec	sens
S-L	67	42	64	57
Cornell	67	67	72	69
R-E	100	8	100	43

Romhilt-Estes index at their conventional cut-off values are shown in Table 2.

An example of the performance of the MCG strain index is shown in Fig. 3. At an optimal cut-off value of 90°, sensitivity in male subjects was 81% at 72% specificity. In females the corresponding values were 64% and 83%, respectively.

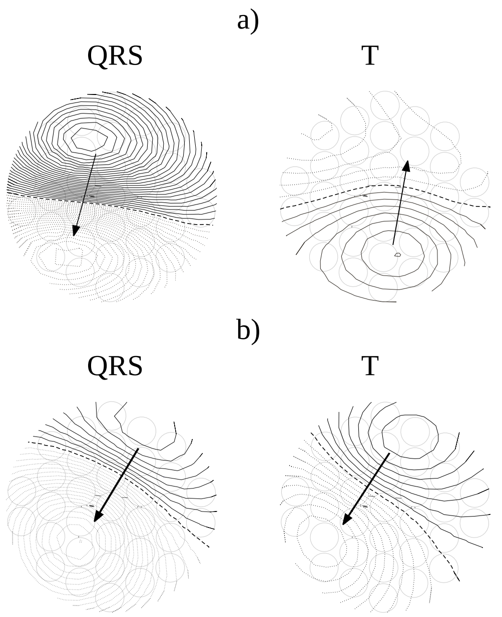

Figure 3: *MCG strain. An example of the isointegral maps over QRS complex and T-wave.* a) *Male subject, LVM/BSA 178 g/m^2, MCG strain index 170°.* b) *Male subject, LVM/BSA 91 g/m^2, MCG strain index 2°. In isointegral maps contour steps are 1.0 pT for QRS maps and 0.5 pT for T-wave maps.*

4 Discussion

The results of this study indicate that the combined de- and repolarisation analysis might improve detection of LVH with MCG. Of the MCG indices studied, the index combining T-wave integral and QRS area performed best in the diagnosis of LVH in this patient population. Contrary to other indices, electrocardiographic or magnetocardiographic, it was sensitive both in females and males. The performance of the MCG strain index was also relatively good both in males and females.

In general, the performance of the MCG indices was at least as good as that of ECG indices. In females, the values of sensitivity at matched specificity were considerably higher for the MCG indices than for the ECG indices. In males, the sensitivities were of the same order for MCG and ECG.

The preliminary findings presented here are promising. An analysis of the results with receiver operating characteristic (ROC) curves, which would better clarify the differences in the performance of MCG and ECG indices, would require a larger patient population.

As the magnetic field strength attenuates with distance, scaling the signals by the distance from the center of the heart to the cardiomagnetometer could lead to better performance of MCG in detection of LVH. The distance could be obtained from chest X-ray or magnetic resonance images (MRI). Also, more accurate reference for LVM, compared to echocardiogram, could be obtained from MRI.

References

[1] D. Levy, K.M. Anderson, D.D. Savage, W.B. Kannel, J.C. Christiansen, W.P. Castelli: ”Electrocardiographically Detected Left Ventricular Hypertrophy: Prevalence and Risk Factors (The Framingham Heart Study)”. *Ann Int Med* **108**, 7–13, 1988.

[2] D. Levy, S.B. Labib, K.M. Anderson, J.C. Christiansen, W.B. Kannel, W.P. Castelli: ”Determinants of Sensitivity and Specificity of Electrocardiographic Criteria for Left Ventricular Hypertrophy”. *Circulation* **81**(3), 815–820, 1990.

[3] R.B. Devereux, N. Reichek: ”Echocardiographic Determination of Left Ventricular Mass in Man. Anatomic Validation of the Method”. *Circulation* **55**(4), 613–618, 1977.

[4] K. Fujino, M. Sumi, K. Saito, M. Murakami, T. Higuchi, Y. Nakaya, H. Mori: ”Magnetocardiograms of Patients with Left Ventricular Overloading Recorded with a Second-Derivative SQUID Gradiometer”. *J Electrocardiol* **17**(3), 219–228, 1984.

[5] O.S. Oja, J. Nousiainen, K. Niemelä, A. Uusitalo, J. Malmivuo: ”Magnetocardiogram in Left Ventricular Hypertrophy”, in *Proc. 6th International Conference on Biomagnetism*, Tokyo, 1987, pp. 290–293.

[6] W. Moshage, S. Achenbach, A. Weikl, K. Göhl, K. Bachmann, K. Abraham-Fuchs, W. Härer, S. Schneider: ”Clinical Magnetocardiography: Experience with a Biomagnetic Multichannel System”. *Int J Card Im* **7**, 217–223, 1991.

[7] P. Takala, J. Montonen, J. Aalto, M. Mäkijärvi, J. Nenonen, Y. Yildirim, M.S. Nieminen, T. Katila: ”Magnetocardiographic Assessment of Left Ventricular Hypertrophy: Correlation with Echocardiography”, in *Proc. 10th International Conference on Biomagnetism*, Santa Fe, 1996, pp. 558–561.

[8] J.A. Milliken: ”Enlargement and Hypertrophy” in *Comprehensive Electrocardiology, Vol. 1*, ed. MacFarlane, Lawrie; Pergamon Press 1989, pp. 631–670.

[9] R.B. Devereux, N. Reichek: ”Repolarization Abnormalities of Left Ventricular Hypertrophy. Clinical, Echocardiographic and Hemodynamic Correlates”. *J Electrocardiol* **15**(1), 47–54, 1982.

[10] P. Siltanen: ”Magnetocardiography” in *Comprehensive Electrocardiology, Vol. 2*, ed. MacFarlane, Lawrie; Pergamon Press 1989, pp. 1405–1438.

[11] J. Montonen, A. Ahonen, M. Hämäläinen, R. Ilmoniemi, P. Laine, J. Nenonen, M. Paavola, K. Simelius, J. Simola, T. Katila: ”Magnetocardiographic Functional Imaging Studies in the BioMag Laboratory”, in. *Proc. 10th International Conference on Biomagnetism*, Santa Fe, 1996, pp. 494–497.

[12] J. Numminen, S. Ahlfors, R. Ilmoniemi, J. Montonen, J. Nenonen: ”Transformation of Multichannel Magnetocadiographic Signals to Standard Grid Form”. *IEEE Trans Biomed Eng* **42**, 72–78, 1995.

[13] M.B. Simson: ”Use of Signals in the Terminal QRS Complex to Identify Patients with Ventricular Tachycardia After Myocardial Infarction”. *Circulation* **64**(2), 235–242, 1981.

[14] L. Oikarinen, M. Paavola, J. Montonen, M. Viitasalo, M. Mäkijärvi, L. Toivonen, T. Katila: ”Magnetocardiographic QT interval Dispersion in Postmyocardial Infarction Patients with Sustained Ventricular Tachycardia: Validation of Automated Measurements”. *PACE* **21**, 1934–1942, 1998.

[15] H. Hänninen, P. Takala, M. Mäkijärvi, J. Montonen, P. Korhonen, L. Oikarinen, J. Nenonen, T. Katila, L. Toivonen: ”Detection of Exercise-Induced Myocardial Ischemia by Multichannel Magnetocardiography in Single Vessel Coronary Artery Disease” *A.N.E.* **5**, 2000.